Wave Breaking, Infragravity Waves, And Sediment Transport In The Nearshore

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LONG-TERM GOALS

The long-term goals of this research are to understand and model the spatial and temporal transformation of wave breaking in the surf zone of natural beaches, and to predict the effect of wave breaking on the forcing of mean and oscillatory flow, sediment transport, and the evolution of large scale topography.

OBJECTIVES

(1) Improved modeling of wave breaking patterns observed in the surf zone, and the effect of wave breaking on the spatial distribution of mean flow and sediment transport.

(2) Improved understanding of the cross-shore variation in infragravity waves and their impact on large scale sediment transport patterns

APPROACH

The difficult problem of understanding wave dissipation in the nearshore is approached through field observations obtained across a variety of beach profiles and under a wide range of wave conditions. Data are obtained remotely from video recordings of the surf zone, and image processing techniques are used to detect and quantify wave breaking over spatial and temporal scales ranging 10-1000 meters and 10-10000 seconds. The observed spatial distribution of ensemble-averaged wave breaking patterns are used to improve numerical dissipation estimates, and subsequently applied to parametric models of incident wave energy transformation and mean current forcing within the surf zone. Quantification of the fraction of surface gravity wave energy at infragravity frequencies is approached through a combination of theory and collaborative *in situ* observations of wave pressures and currents spanning the surf zone. The relationship of incident wave breaking and infragravity waves to sediment transport is being pursued through co-located subaerial video observations and *in situ* measurements of wave pressure and velocity, sediment concentration, turbulence, and void fraction.

WORK COMPLETED

Observations of wave breaking at a number of shore-normal transects at several alongshore locations and extending from the shoreline to beyond the width of the surf zone, were made continuously for over 2 months during the 1997 SandyDuck experiment utilizing both daytime and intensified night-time video cameras. The position and time of wave breaking occurrences were measured using digital

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image processing techniques in which image pixels – containing the luminance intensity of light reflected off the sea surface – are sampled in a dense shore-normal transect (called timestacks) extending from the dry beach to well outside the surf zone. During SandyDuck, timestacks were collected continuously at the same location as the instrumented cross-shore, and are used to quantify the spatial and temporal scales of wave breaking distributions on time scales ranging from individual breaking, O(10-*sec*), to single and multiple wave groups, O(0.1-1-*hour*), tides, O(1-*hour*), and changes in the wind and wave conditions, O(1-10-*day*). Simultaneous *in situ* measurement of properties of the hydrodynamics, sediment transport, and dissipation were made by SandyDuck collaborators.

Observations of a cross-shore array of bi-directional current meters and bottom wave pressure gauges from the 1990 Delilah field experiment are used to verify theoretical relationships for a broad-banded edge and leaky wave field, and to separate gravity and shear wave contributions to infragravity energy distributions across a barred surf zone.

RESULTS

We have developed empirical algorithms to identify the location of individual breakers in timestack imagery (Figure 1; Athwal and Lippmann, 1998). The precision of identifying the leading edge of the breakers is estimated to be generally 1 pixel. The accuracy in detecting breakers from other non breaking features, such as residual foam left after the passage of a breaking wave, is estimated to be 1-2% of the total breaking waves for most days. The analyzed timestacks are used to compute statistical representations of the breaking wave field. The breaking frequency was observed to be strongly tidally modulated, with breaking patterns moving onshore and offshore as the water depth increased and decreased, respectively, with the tide, consistent with predictions from roller-based energy models (Lippmann, *et al.*, 1996; Lippmann and Thornton, 1999b) and previous observations of longshore currents (Thornton and Kim, 1993).

The breaking frequency can be normalized by the total number of waves obtained from incident wave pressure measured outside the surf zone to yield the fraction of the wave field that is breaking, Q, and used to calibrate ensemble-averaged wave transformation models. Large 10-50% variations were observed in Q with time scales on the order of 15-30-*min*, much longer than typical wave groups (with periods of a few minutes) and much shorter than tidal periods or changes in the wind and wave climate (Figure 2; Lippmann, *et al.*, 1998b). Similar coincident 10-50% variations were observed in the root-mean-square wave height and wave asymmetry. Although the origin of the modulations in wave properties are yet unknown, these variations drive fluctuations in the mean response of the nearshore, such as that observed in the cross-shore set-up profile.

Surface shear stress profiles computed from wave transformation models calibrated with observations of Q, are used in the momentum balance to model the generation and variation of set-up (Reniers, *et al.*, 1999), vertical profiles of undertow and mean longshore currents (Garcez Faria, *et al.*, 1998; 1999a), and the horizontal distribution of mean longshore currents (Garcez Faria, *et al.*, 1999b). This work has verified that inclusion of wave rollers in the energy and momentum balance is necessary to accurately represent the wave forcing. An important result is that bottom drag coefficients used for calculating vertical mean current profiles are consistent with coefficients used for computing horizontal mean flow profiles.

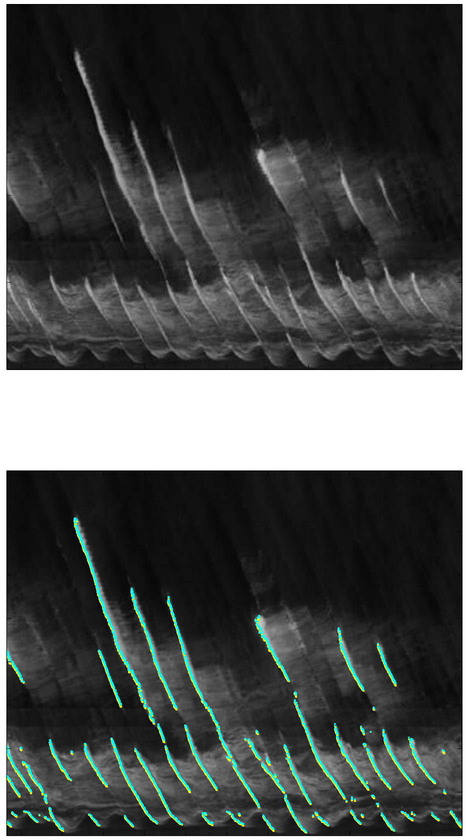
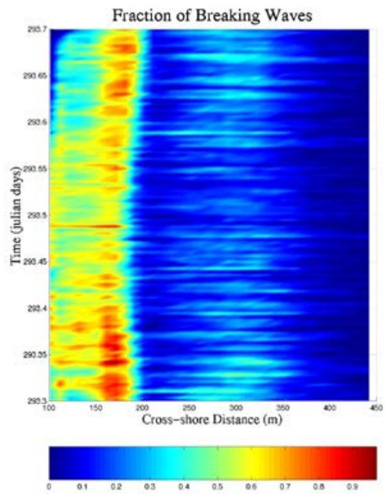
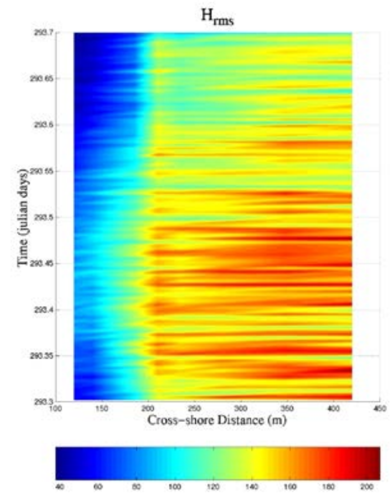


Figure 1. (Upper Panel) Example 3-min timestack showing the location and time of breaking waves and bores in the surf zone. The vertical axis is cross-shore distance along a shore-normal transect located approximately 400-m from the camera, and has mean resolution of approximately 0.25-m^2 per pixel. Waves from the sea (top of the images) move toward the right as they propagate shoreward. Breaking waves are clearly visible as white streaks along the wave paths. (Lower panel) Same timestack with breaking waves identified with the colored dots. The locations of breaking waves are determined using automated image processing edge detection algorithms (Athwal and Lippmann, 1998).

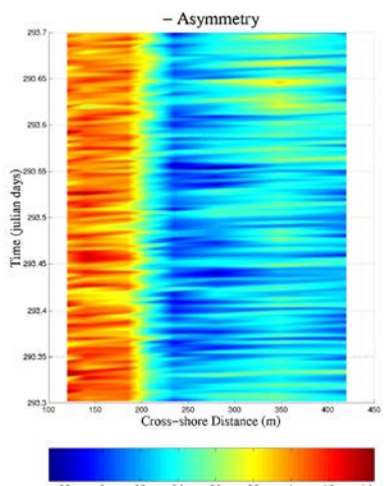
A coupled system of turbulent and diffusive transport equations to predict theoretically the vertical variation of suspended sediment concentration in the water column was developed in the mid 1980's (Deigaard, *et al.*, 1986). The generation of turbulent kinetic energy (TKE) in the bottom and surface boundary layers was included in the production term and used to examine the enhanced effects of wave breaking on suspended sediment concentration. Although comparisons were made favorably to early observations of suspended sediment, a robust field examination has not been possible until recently (*e.g.*, the 1997 SandyDuck experiment), because the combination of accurate co-located measurements of turbulence, suspended sediment concentration, and wave breaking were not available. As part of ongoing collaborative research we plan to verify the simple TKE and diffusion transport equations, and to examine with field data the effect of ensemble-averaged wave breaking on sediment suspension. The production of TKE in the surface boundary layer is determined from the average surface shear stress resulting from a field calibrated energy transformation model that includes the localized and advection effects of wave breaking observations. The spatial and temporal variation of wave breaking is correlated with the observed vertical variation of turbulence intensities, void fraction, and sediment concentration measured *in situ* (PI's Thornton & Stanton; Hay & Bowen).



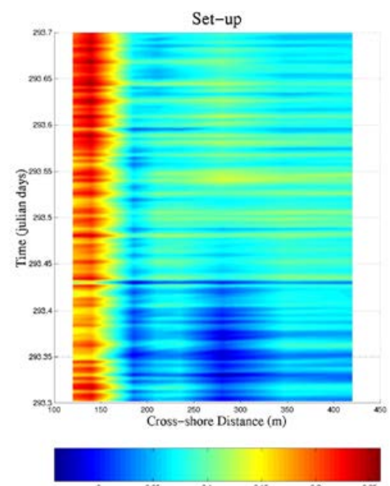
(A) Scale in non-dimensional fraction.



(B) Scale in centimeters.



(C) Scale in normalized minus asymmetry.



(D) Scale in centimeters.

Figure 2. (A) The spatial and temporal fraction of breaking waves, Q, determined over successive 5-min intervals from timestacks spanning a 10-hour period on 21 October 1997 during SandyDuck. Observations extend from the shoreline (cross-shore coordinate 120-m) to over 300-m offshore. The inner sand bar crest is located at about cross-shore coordinate 195-m. Clearly shown are 10-50% fluctuations in Q with time scales of order 15-30-min, much longer than typical wave groups of order a few minutes. Also shown for the same 10-hour period are the spatial and temporal variation in (B) root-mean-square wave height, (C) minus normalized (by variance to the 3/2 power) asymmetry, and (D) set-up. The variation in wave properties over the barred profile also show 10-50% fluctuations at similar time scales as observed in Q. The value and color shading are shown by the color-bars at the bottom of each figure.

Subsequent to mobilization and suspension is the horizontal transport of sediment (sediment flux), dependent on the co-spectrum of fluid velocities and sediment concentration. Field data have been used to determine the relative importance of mean flow, shoreward progressive incident waves, and longer period infragravity motions to sediment flux (*e.g.*, Hanes and Huntley, 1986). Under energetic wave conditions, observed co-spectra indicate that infragravity waves are coherent with low frequency

variations in sediment concentration (*e.g.*, Beach and Sternberg, 1988). Analysis from the 1990 Delilah experiment indicate that infragravity energy is locally maximum over the shallows of the bar, and appears to be more strongly amplified when the morphology becomes three-dimensional (Lippmann, *et al.*, 1998a). The coincidence of increased turbulence by wave breaking suggests that three-dimensional bar evolution may be linked to the combined effects of breaking induced sediment mobilization and suspension and subsequent transport by energetic infragravity waves over the bar.

A cross-shore array of 9 co-located pressure sensors and bi-directional current meters from the 1990 Delilah experiment (PI Thornton), extending from the shoreline to approximately 4.5-*m* depth, were used to used to estimate the relative contributions of gravity waves and instabilities of the longshore current (shear waves) to motions in the infragravity band (Lippmann, *et al.*, 1999). Outside the surf zone where the shear of the longshore current is relatively weak, the observed total infragravity velocity to pressure variance ratios (normalized by g/h) are approximately equal to 1, consistent with an infragravity spectrum dominated by gravity (edge and/or leaky) waves. Inside the surf zone where the longshore currents are strongly sheared, these normalized ratios are much larger, up to 8 on some occasions, indicating that shear waves contribute as much as 75% of the velocity variance in the infragravity band. Energetic shear waves are confined to the (often) narrow region of strong shear on the seaward side of the longshore current maximum, and their cross-shore structure appears to be insensitive to the beach profile, consistent with the theoretical predictions by Bowen and Holman (1989). During low-energy incident wave conditions, infragravity pressure variance decreases with increasing water depth qualitatively consistent with the theoretically predicted unshoaling and trapping of gravity waves. However, during high-energy incident wave conditions, the observed infragravity pressure variances are nearly uniform across the surf zone, suggesting strong scattering effects in a wide surf zone (Lippmann, *et al.*, 1998a).

IMPACT/APPLICATIONS

Wave breaking is the principal driving force for currents, mean water level changes, and low frequency oscillatory motions within the surf zone, and is also believed to be of order one importance in sediment transport and large scale sand bar evolution. However, simple parameterizations needed to describe the complicated dissipative mechanisms have not generally been guided by observations. Only with recent advances in remote (*e.g.*, video, acoustic, microwave, infrared, radar) and *in situ* (*e.g.*, optical, acoustic, conductivity) instrumentation, has quantifying the breaking process been possible. Improvements in the sampling and modeling of wave breaking should lead to much improved understanding of wave breaking and its dynamical implications.

TRANSITIONS

Our video techniques developed as part of this research have been used to develop a quantitative aerial video system used in regional studies of large scale sand bar evolution along large lengths of U. S. coastlines (PI's Lippmann, Haines, and Sallenger).

RELATED PROJECTS

Video data analysis of the 1990 Delilah, 1994 Duck94, 1996 MBBE, and 1997 SandyDuck experiments have been examined in collaboration with other ONR-funded scientists making *in situ* observations of wave and current properties, turbulence, sediment suspension, large and small scale bathymetry, and bubble properties and void fraction.

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